

A SM Singlet Scalar as Dark Matter

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In this work we investigate the possibility that a simple extension of the Standard Model (SM) can be the dark matter of the universe. We postulate the existence of a scalar field singlet like the Higgs as an extra term in the SM Lagrangian. We find that from the astrophysical point of view a very small mass and self-interaction is more convenient to agree with observations and from particle detectors observations we do not see any essential constrain to this settings. Thus, we conclude that a scalar field singlet with a small mass and self-interaction is a good candidate to be the nature of the dark matter.

INTRODUCTION

In the last time the most accepted candidates to be the dark matter of the universe have been ruled out by observations. The supersymmetric candidate have been extremely constrained by the LUX [1] detector and recently the axion field seems to be in tension with the BICEP2 results [2]. The accepted scientific paradigm for understanding the evolution of the universe is based on the theory of general relativity and the standard model of particles. Nevertheless, the discovery that the universe is filled out in more than 96% with two unknown kind of matters is putting these two theories in alert. Nowadays there is no doubt that we need to modify or extend one or both of these theories in order to explain the existence of the dark matter (DM) and the dark energy. Of course, the first idea is to modify one of them. There are hundreds of papers studying the modifications of these theories in order to give one explanation of these two kind of matters. The modification of the standard model give rise to the existence of new particles, the most accepted candidates are neutralinos, gravitinos, higgsinos, etc. From the modification of the theory of general relativity we also have several very interesting proposals. There is a third way to explain the existence of the dark sector of the universe. We can also postulate that there exist extra interactions in the universe, besides the strong, weak and electromagnetic fundamental interactions in the standard model, all of them of spin one, and the gravitational interaction of spin two. In this work we propose to explore this way supposing that the DM is the consequence of the existence of a new interaction in the universe. If this is the case, this interaction needs to be a boson. We start with the most simple case of an interaction of spin zero. It must be of long range only, but it must let the rest of the interactions intact at small scales. This implies that the mass of this zero boson is very small. And it must interact very tiny or not at all with the rest of the matter. If this is the case, we have to add to the Lagrangian of the standard model plus general relativity the contribution of this interaction as

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu \Phi)^2 + V + \alpha \mathcal{L}_{Int} \quad (1)$$

where \mathcal{L}_{GR} represents the Lagrangian of General Relativity, \mathcal{L}_{SM} the one of the standard model and \mathcal{L}_{Int} the Lagrangian for the interaction between matter and the scalar field Φ . In order that the scalar field mimics the DM, it is convenient that the scalar field potential V remains convex. The simplest potential with this features is the “Higgs” potential $V = -1/2m^2\Phi^2 + \lambda/4\Phi^4 + \dots$. For simplicity we can start with a real scalar field, but the results presented here are also valid for a complex one.

Observe that the scalar field in Lagrangian (1) could be interpreted as an extra particle in the standard model as well. In any case, both interpretations of this particle are a very simple modification of the standard model of particles.

The main goal of this work is to constrain the values of the three constants of this model m , λ and α using actual observations in particle physics and in astrophysics.

ASTROPHYSICAL CONTRAINS

From the astrophysical point of view this scalar field can be constrained using the resent observations of the Planck satellite, the supernova observations, the rotation curves of galaxies, etc.

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We start analyzing the behavior of the scalar field at cosmological scales. The idea is the following, at very high temperature the scalar field interacts with the rest of matter. This interaction can be mimicked supposing that the scalar field lies in a thermal bath. The scalar field potential can be approximated in a thermal bath at one loop as

$$V = \frac{\lambda}{4} \left(\Phi^2 - \frac{m^2}{\lambda} \right)^2 + \frac{1}{8} T^2 \Phi^2 - \frac{\pi^2}{90} T^4 \quad (2)$$

where T is the temperature of the thermal bath. This ‘‘Higgs’’ potential is very well known, it is convex when T is bigger than the symmetry breaking temperature $T_{SB} = 2m/\sqrt{\lambda}$, and it has the mexican hat shape when $T < T_{SB}$. As the universe expands, it reduces the decoupling temperature of the scalar field with the rest of matter. As the temperature keeps going down, the scalar field reduces the temperature of symmetry breaking at T_{SB} , the Z_2 symmetry breaks down and the scalar field goes into the second minimum of the potential V at $\Phi_{min} = \sqrt{m^2/\lambda - T^2/4} = 1/2\sqrt{T_{SB}^2 - T^2}$. The scalar field starts to oscillate around the second minimum with a frequency $\sim m$. Here it is convenient to analyze the dynamic of the scalar field moving the origin of potential to the new minimum using the transformation $\Phi \rightarrow \Phi - \Phi_{min}$, such that we can neglect the higher order terms, thus the potential V in this new coordinates looks like a Φ^2 scalar field potential. The mass M of the scalar field at this point is $M = \sqrt{2}m$.

Thus, potential V guarantees that the scalar field stabilizes oscillating around its second minimum. In the oscillation state the scalar field behaves as dust and it mimics very well the Cold Dark Matter (CDM). As in the case of the CDM, small fluctuations of the scalar field collapse, the size of the collapse depends on the mass of the scalar field. For a big mass M , it forms small stars and for small mass M it forms big stars, in other words, gravity confines the scalar field in specific regions where the scalar field starts to collapse. Because of the tiny coupling constant the scalar field behaves as an ideal gas, which critical temperature of condensation is

$$T_c = \frac{2\pi}{M^{5/3}} \left(\frac{\rho}{2.612} \right)^{\frac{2}{3}} \quad (3)$$

where ρ is the density of the scalar field in the specific volume v where it is confined. For a tiny mass of order of eV the critical mass of condensation is of the order of TeV. Thus we expect that the scalar field forms Bose-Einstein Condensates (BEC) very early in the universe. Furthermore, the critical mass of collapse is

$$M_c = 0.06\sqrt{\lambda} \frac{m_{pl}^3}{M^2} \quad (4)$$

where m_{pl} is the Planck mass. This critical mass M_c can be interpreted as a maximal mass of collapse, that means that the scalar field will form self-gravitating objects with mass M_c and lower. Thus, for example, axions have a mass of the order of $M \sim 10^{-3}$ eV and a self-coupling constant $\lambda \sim 10^8$. They form stars with the mass of a mountain and so small as a football ball, therefore they will behave as CDM and have the same problems as CDM. In this work we want to avoid these problems, here we will suppose that the mass M and the self-interaction's parameter λ are very small, for example M might be of the order of eV, like the neutrinos and $\lambda \sim 10^{-6}$, such that the critical mass of collapse is like the halo of a galaxy. Thus, each BEC star made of this scalar field will form a galaxy. That means, the main difference of this hypothesis with the axions is just this, namely, the CDM galaxies form by collapse of dust made of a heavy or a heavy clump of particles, while the scalar field galaxies form by condensation, the scalar field freezes and forms the halo of a galaxy. Thus, the important difference between these two paradigms is that the galaxies in CDM have a density profile close to the center of the galaxy like $\rho \sim 1/r$, where r is the distance measured from the center. The CDM galaxies have a cusp central density profile. It is well known that the BEC is completely regular at the center, in this context they generate core density profiles.

On the other hand, with this coupling constant and mass, scalar fields do not have any problem with CMB observations. This, together with the fact that the scalar field behaves like dust, i.e., like CDM at cosmological scales, guarantees that the mass power spectrum and the angular power spectrum are the same as in the CDM model.

Nevertheless, there is a second fundamental difference between CDM and this model. Galaxies are hierarchically formed in the traditional CDM model, small galaxies merge with other ones and form bigger galaxies, till they get the size they have today. While they are formed by condensation in the case of the scalar field. It means that in the scalar field paradigm galaxies will form very early, at least much earlier than in the case of the CDM model. Thus, if the scalar field with these parameters is the DM in the universe, we have to see well formed galaxies at high redshifts and they must be core in the center, while if some particle like the WIMPs is the DM, we have to see that galaxies form from redshifts $z \sim 6$ and they must have a cusp central density profile. Summarizing, the scalar field and the CDM models behave in the same way at cosmological scales, but at galactic scales they have some differences. Two of these differences are that scalar field halos are core and CDM ones are cusp and that scalar field halos form much earlier than the CDM ones.

PARTICLE PHYSICS CONSTRAINS

Since the rise of the SM most of the proposals to extend the model have been based on generalizations and/or higher symmetries which could include new fields in a constrained scheme containing the basic features of the SM. The recent negative results in the search for several constrained SUSY models and scenarios in the LHC have changed the idea that the best theoretically motivated models are the most appealing and have raised serious doubts if, for example SUSY, cure more problems than those which create. The alternative approach is to propose an entirely phenomenological model solving the DM problem and consistent with all the experimental data available (astrophysical, cosmological, from colliders, etc.) and verify if it is falsifiable. The present idea it is not new, it has been proposed several times under different names (darkon, phion, little higgs etc.) and in the current situation of very new data measurements from LHC and Plank, the review of this simplest model is compulsory.

Vacuum and symmetry breaking pattern

The first condition for this model is that it must not have a visible influence on the way the Standard Model Higgs breaks the EW symmetry. The relations that have to be held in order to have the new potential bounded from below to ensure the existence of a vacuum can be seen elsewhere. The conditions to preserve the role of the SM Higgs in the EW symmetry break pattern are $\langle S \rangle = 0$, $0 < -m_0^2 < v_{EW}^2 \sqrt{\lambda_h \lambda_S}$. If we use the conventional shift to the vacuum value for h to represent the physical Higgs having mass $m_h^2 = \lambda_h v_{EW}^2$ the potential dependent of the new scalar can be written as

$$V = \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \frac{\lambda_S}{4}S^4 + \lambda v_{EW}S^2h + \frac{\lambda}{2}S^2h^2 \quad (5)$$

with the S mass being $m_S^2 = m_0^2 + \lambda v_{EW}^2$. The prejudice some years ago was that the range for this mass was from a few to a few hundred GeV in order to have cold dark matter, this is not a consensus anymore. There is another prejudice from the latter equation, in the cases for very low masses for the new scalar there is a new fine tuning to be explained. Being not the first or the most relevant fine tuning in field theory the model can allow it.

LHC Measurements

There is a wide program in both LHC experiments, ATLAS and CMS, to search for Dark Matter even if it can not be seen inside the detector. These searches rely in the capabilities to measure the Transverse Missing Energy and reconstruct the events that have the DM at the end of the cascade. The masses we are estimating for the model are far from the best sensitivity of both experiments. Nevertheless the scalar proposed couples with the Higgs Boson and should be part of its invisible width. The measurements of the Higgs boson couplings at the LHC allow to constrain the contribution of an invisible decay to the total width.

An extensive fit to the recent data has been performed by Espinosa *et al.* [7] where they obtained that $Br_{inv} < 0.37(0.40)$ for $m_h = 125(126)$ GeV at 95% C.L. The best fit gives a value of $Br_{inv} = 0.05$ with 95% C.L.

The $h \rightarrow SS$ decay width is given by

$$\Gamma(h \rightarrow SS) = \frac{1}{8\pi} \frac{\lambda^2 v_{EW}^2}{m_h} \sqrt{1 - \left(\frac{2m_S}{m_h}\right)^2}. \quad (6)$$

Using either the best fit or the limit for the branching ratio of the Higgs' Invisible width and the expression of the Higgs' width to scalars we can find the allowed region for coupling and mass combinations.

The limit on the Higgs' Invisible width can be interpreted as

$$\lambda^2 \sqrt{1 - \frac{4m_s^2}{(125 \text{ GeV})^2}} < 76.83 \text{ eV} \quad (7)$$

and it is not a closed region(see Fig. 1).

We can use the mentioned limit from relic density on the coupling $\lambda \geq 10^{-8}$ to obtain the limit on $m_S > 62.5$ GeV.

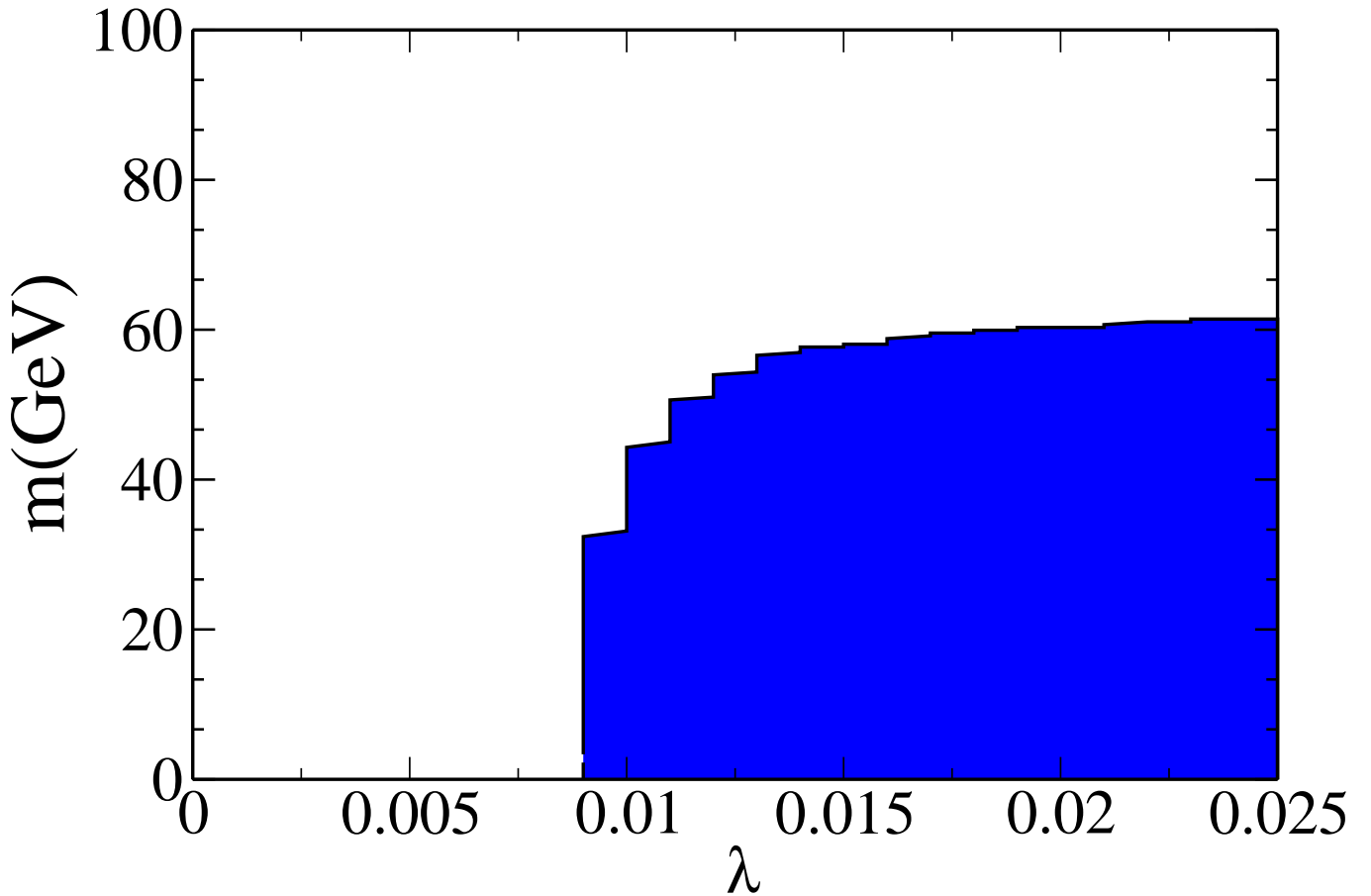


FIG. 1: Exclusion region (in blue) in the λ , mass plane from the Higgs invisible width.

Dark Matter Direct Searches

The nucleon-scalar elastic scattering cross section can be also obtained for a parameters space region and compare it with the current limits from WIMP Searches.

From [6] we can verify that the expression

$$\sigma_{el}(nucleon) \approx \lambda^2 \left(\frac{100 GeV}{m_h} \right)^4 \left(\frac{50 GeV}{m_S} \right)^2 (20 \times 10^{-42} cm^2) \quad (8)$$

could be useful to find independent allowed combinations of m_S and λ .

Recently some of the proposed experiments have quoted to plan to reach $10^{-43} cm^2$ for this cross section. This cross section corresponds to model dependent parameter combinations specific exclusions.

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